

## EOS Microwave Limb Sounder Observations of “frozen-in” anticyclonic air in Arctic summer

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**Abstract.** A previously unreported phenomenon, a “frozen-in” anticyclone (FrIAC) after the 2005 Arctic spring vortex breakup, was discovered in Earth Observing System (EOS) Microwave Limb Sounder (MLS) long-lived trace gas data. A tongue of low-latitude (high-N<sub>2</sub>O, low-H<sub>2</sub>O) air was drawn into high-latitudes and confined in a tight anticyclone, then advected intact in the summer easterlies through late August. A similar feature in O<sub>3</sub> disappeared by early April as a result of chemical processes. The FrIAC was initially advected upright at nearly the same speed at all levels from ~660 to 1300 K (~25–45 km); increasing vertical wind shear after early June tilted the FrIAC and weakened it at higher levels. The associated feature in PV disappears by early June; transport calculations also fail to reproduce the remarkable persistence of the FrIAC, suggesting deficiencies in summer high-latitude winds. The historical PV record suggests that this phenomenon may have occurred several times before. The lack of a persistent signature in O<sub>3</sub> or PV, along with its small size and rapid motion, make it unlikely that a FrIAC could have been reliably identified without hemispheric daily long-lived trace gas profiles such as those from EOS MLS.

### 1. Introduction

Several modeling studies have examined the evolution of vortex remnants after the springtime breakup. *Hess* [1991] postulated that tracer variance generated by wave breaking during the vortex breakup can be “frozen in”, that is, remnants of vortex air are advected intact by the summer easterlies, in which the shears (horizontal and vertical) are too weak to reduce such anomalies to the fine scale required for them to be dispersed by diffusion. *Orsolini* [2001] showed such Arctic vortex debris persisting into August in a chemical transport model (CTM) simulation, and noted that long-lived trace gas observations to verify his results were unavailable. *Manney et al.* [2005] recently used long-lived trace gas data from the Earth Observing System (EOS) Microwave Limb Sounder (MLS) to examine the 2004 Antarctic vortex breakup, and showed that remnants of vortex air could be followed for over a month after the relatively grad-

ual vortex breakup in the middle stratosphere.

In the Arctic, the vortex breakup is typically much earlier and more abrupt than that in the Antarctic [e.g., *Waugh and Randel*, 1999], often being triggered by stratospheric sudden warming events. The 2005 vortex broke up in a “major final warming” (MFW), that is, a major warming leading directly into the final warming without a general return to westerlies in high latitudes in between [e.g. *Labitzke and Collaborators*, 2002], beginning in early March. As a result of the vigorous wave activity at the time of the final warming, a strong intense anticyclone comprising air drawn up from the tropics formed at high latitude. We detail below the EOS MLS long-lived trace gas observations during the vortex breakup and through the summer. In addition to confirmation of frozen-in vortex remnants, these observations show the development and persistence through summer of a strong coherent remnant of air from the high-latitude anticyclone, a phenomenon that has not previously been reported.

We use version 1.51 (the first publicly released version) N<sub>2</sub>O, H<sub>2</sub>O and O<sub>3</sub> data from MLS. The vertical resolution is ~4 km, ~5 km, and ~3 km, and estimated precisions

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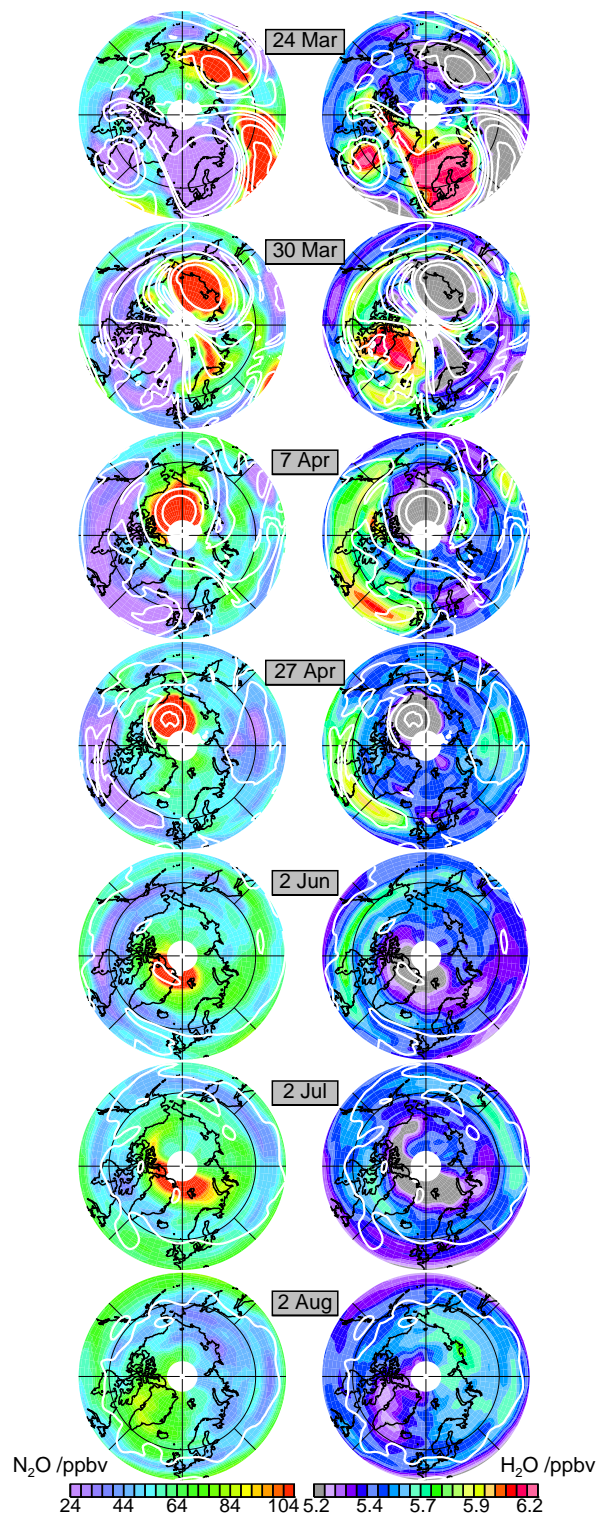
$\sim 20\text{--}30$  ppbv,  $\sim 0.05\text{--}0.1$  ppmv, and  $\sim 0.2\text{--}0.3$  ppmv, for  $\text{N}_2\text{O}$ ,  $\text{H}_2\text{O}$  and  $\text{O}_3$ , respectively [Froidevaux et al., 2005]. NASA's Global Modeling and Assimilation Office Goddard Earth Observing System, Version 4.0.3 (GEOS-4) [Bloom et al., 2005], European Centre for Medium Range Weather Forecasting (ECMWF), and UK Met Office (MO) meteorological analyses are used to examine winds, potential vorticity (PV), and for transport calculations. Results are shown from a SLIMCAT [Chipperfield, 1999] 3-dimensional (3D) CTM run driven with the MO winds, run in near real time and sampled at the MLS observation locations.

## 2. The Evolution of Vortex and Anticyclone Air in Spring and Summer 2005

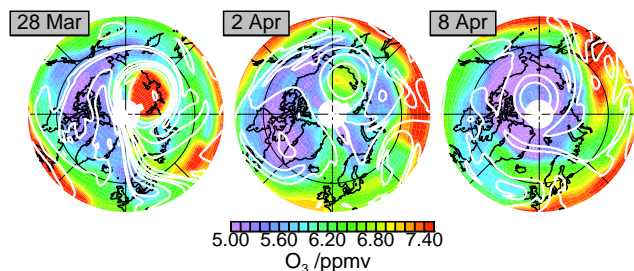
Figure 1 shows 850 K maps of MLS  $\text{N}_2\text{O}$  and  $\text{H}_2\text{O}$  from late March through early August. In the disturbed conditions during and after the MFW, large tongues of low-latitude air are drawn up around the polar vortex and entrained into the anticyclone. One such tongue, seen on 24 March, was pulled into a very strong anticyclone at high latitude (e.g., 30 March), bringing with it the high  $\text{N}_2\text{O}$  and low  $\text{H}_2\text{O}$  characteristic of the tropics. After early April, this enclosed air mass was advected relatively unchanged by the summer easterlies (e.g., 7 April through 2 June). While it weakens somewhat after early June, the feature is discernible in maps until mid-August. Fragments of vortex air can also be detected through at least mid-July, near  $40\text{--}60^\circ\text{N}$  (e.g.,  $90\text{--}180^\circ\text{E}$  on 2 July); later (e.g., 2 August), these are sufficiently diffuse that their identification with vortex air is uncertain. The vortex remnants are also advected by the summer easterlies, moving more slowly than the anticyclonic feature in the weaker winds at lower latitudes. “Frozen-in” vortex remnants have previously been reported in models [e.g., Hess, 1991; Orsolini, 2001], with some observational evidence [e.g., Hess and Holton, 1985; Manney et al., 2005], and the anticyclonic feature appears to be analogous to these; we refer to it hereinafter as a “frozen-in anticyclone” (FrIAC).

A similar feature forms in  $\text{O}_3$  (Figure 2). However, when high ozone from low latitudes is confined in an anticyclone at high latitudes, it quickly relaxes to values characteristic of high latitudes; this is similar to the “low-ozone pocket” phenomenon seen in winter [e.g., Harvey et al., 2004], but relaxation is expected to be even faster in the higher-sunlight springtime conditions.  $\text{O}_3$  is the only stratospheric trace gas for which we have previous extensive, multi-annual, global or hemispheric profile measurements covering Arctic spring and summer. The transience of the FrIAC signature in  $\text{O}_3$  therefore suggests that detection of a FrIAC in previous trace gas observations was unlikely.

Figure 3 shows Hovmöller (time-longitude) plots of MLS



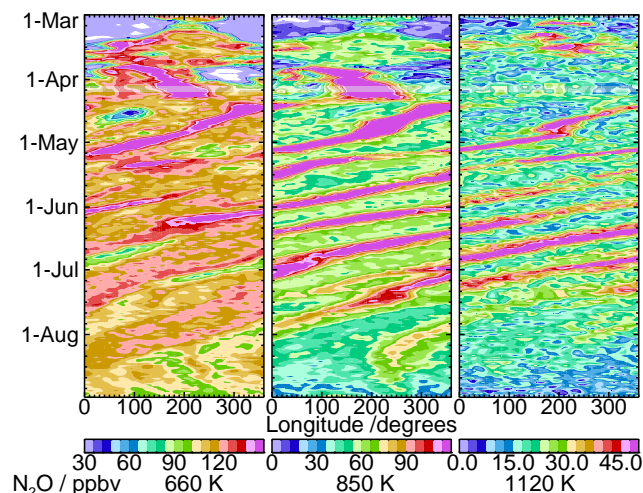
**Figure 1.** Maps of 850 K MLS  $\text{N}_2\text{O}$  and  $\text{H}_2\text{O}$  after the 2005 Arctic vortex breakup. Overlaid contours are scaled PV; fine lines show  $60^\circ\text{N}$  latitude.



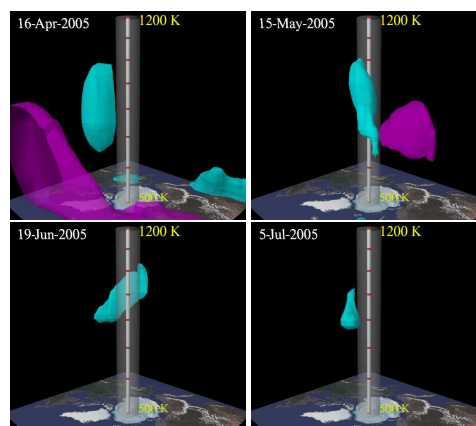
**Figure 2.** As in Figure 1, but for MLS  $O_3$  in March and early April.

$N_2O$  at  $78^\circ N$  for March through August, at 660, 850, and 1120 K. (This and following figures show only  $N_2O$ ; the same features are also clearly apparent in MLS  $H_2O$ .) 660 K is near the lowest level at which a persistent signature of the FrIAC can be detected; 1120 K is near the highest. The FrIAC extends to higher levels ( $\sim 1400$  K) and slightly lower levels ( $\sim 600$  K) in April and May, but is not as persistent at these levels. The formation of the FrIAC is seen clearly: The initial high anomaly after  $\sim 24$  March comes from the tongue drawn up from low latitudes. At this time, the background flow is still westerly, and the feature initially moves slowly eastward; in early April, the mean flow reverses, the FrIAC is advected across the pole (thus, for a short time,  $\sim 8$ – $12$  April, not sampled at  $78^\circ N$ ), and then advected by the easterlies. Examination of GEOS-4 zonal winds indicates that the period (initially,  $\sim 23$ – $25$  days, decreasing to 13–15 days in early May) is consistent with passive advection by the summertime easterlies. Comparison of the three levels indicates that the period of the FrIAC is nearly the same at all levels through early June. This is consistent with very weak vertical wind shears seen in GEOS-4 from early April through early June from about 650 through 1400 K; after early June, vertical wind shear increases below  $\sim 750$  K, and by early July, there are substantial wind shears throughout the stratosphere, with weaker winds at lower levels. Consistent with the changing wind shears, the FrIAC period after late June is slower (faster) at lower (higher) levels. The FrIAC can be identified at all three levels through early August. At 850 K a distinct signature is seen until late August; between 20 and 25 August, 850 K GEOS-4 winds reverse, and at this time the FrIAC stalls and dissipates.

A 3D view of the FrIAC is given in Figure 4; supplementary electronic material contains an animation of this. The isosurfaces show the deviation in  $N_2O$  from a northern hemisphere mean profile averaged over 11 March to 18 July 2005. A larger deviation is used for vortex (low) values, so the vortex does not obscure the view of the FrIAC in its early stages. As seen in Figure 3, the FrIAC is initially upright, with no longitudinal tilt between levels. After mid-May, the



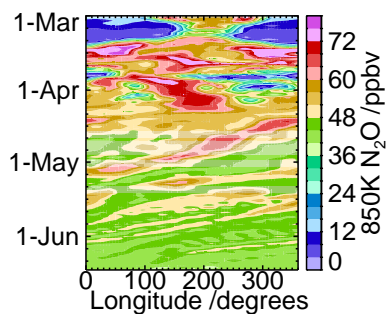
**Figure 3.** Time-longitude (Hovmöller) plots from March through August 2005 of MLS  $N_2O$  at  $78^\circ N$  and (left to right) 660, 850, and 1120 K. Pale stripe shows missing day that has been filled using Kalman smoother.



**Figure 4.** Isosurface plots of  $N_2O$  deviations from northern hemisphere mean profile (see text). Cyan surface, +15 ppbv, shows anticyclone; magenta surface,  $-90$  ppbv, shows vortex remnant. Vertical range is 500 to 1200 K. Supplementary electronic material contains animation for 1 March through 20 July 2005.

FrIAC begins to tilt and weaken at the higher and lower levels. By mid-June, when vertical wind shears are significant, the FrIAC is strongly tilted westward with height, consistent with stronger easterlies at those levels. Even with the mean removed, it is problematic to choose a single isosurface that captures the FrIAC signature at all levels and times, since strong  $N_2O$  gradients also imply differing ranges of variance at different levels. Thus, while this isosurface disappears around mid-July, the FrIAC signature in the midstratosphere persists through most of August (Figure 3).

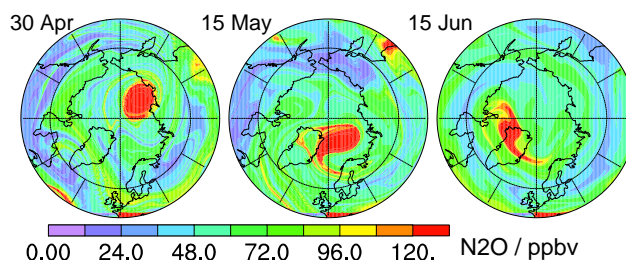
It is of interest to explore how the FrIAC is represented in transport models. Figure 5 shows a Hovmöller plot for



**Figure 5.** Hovmöller plots at 78°N of SLIMCAT 850 K N<sub>2</sub>O from March through mid-June 2005. The contour range is different from that for MLS. Pale stripes show missing days that have been filled with Kalman smoother.

March through mid-June 2005 of N<sub>2</sub>O from the SLIMCAT simulation. Because of deficiencies in initialization and descent in this run, modeled N<sub>2</sub>O gradients are weaker and 850 K values lower than those in the MLS data. Still, the formation and initial evolution of the FrIAC are qualitatively the same as in the data, with a large high-N<sub>2</sub>O anomaly forming, moving slowly eastward until the winds shift in early April, and then being advected with the easterlies. However, by late May, the feature in this simulation weakens and disappears. Examination of SLIMCAT maps (not shown) indicates that the feature is unrealistically sheared out after mid-May. The same behavior is seen in SLIMCAT H<sub>2</sub>O.

Reverse trajectory (RT) calculations [e.g., Sutton *et al.*, 1994; Manney *et al.*, 2000] also reflect unrealistic behavior in modeled transport. RT calculations initialized with MLS N<sub>2</sub>O 16 days prior to the dates in Figure 6 show realistic simulation of the anticyclonic feature through early May, but after that result in a feature that is unrealistically shredded, similar to the behavior in SLIMCAT. The 3D SLIMCAT run was driven with MO winds and the MIDRAD radiation scheme for vertical motions; the RT calculations shown here are 3D runs driven with winds and diabatic heating from GEOS-4. Isentropic (no vertical motion) RT runs were also done using MO, ECMWF, and GEOS-4 winds. In each case, the unrealistic shredding of the FrIAC commenced at approximately the same time, though the details of its dissipation differed. The isentropic GEOS-4 runs produced patterns very similar to those in the 3D runs shown in Figure 6. Consistent results between 3D and isentropic transport calculations using several analyses strongly suggest that the analyzed horizontal winds are unrealistically dispersive at high latitudes in summer. The representation of vortex remnants, at lower latitude in a region of weaker winds, appears to be somewhat more faithful.



**Figure 6.** 850 K N<sub>2</sub>O maps from 16-day RT calculations (see text) initialized with MLS data, and driven with GEOS-4 winds and diabatic heating rates.

### 3. Summary and Discussion

EOS MLS long-lived trace gas observations have led to the discovery of a previously unreported phenomenon. During and after the major final warming in Arctic spring 2005, a tongue of low-latitude air was drawn into the polar regions and confined in a tight, closed anticyclone. When the prevailing winds reversed several days later, this anticyclonic, low latitude air was subsequently advected intact by the summer easterlies, and remained distinct and confined at very high latitudes (70–80°N) through late August in the middle stratosphere. The “frozen-in anticyclone” (FrIAC) initially extended from ~660 to 1300 K (~25–45 km), and was advected at nearly the same speed at all levels through early June. In June and July, vertical wind shears increased, leading to faster advection at higher altitudes, tilting the FrIAC with height and weakening it at higher levels. At 850 K (~30 km), the FrIAC persisted through late August, when easterlies weakened and the feature slowed and dissipated. Transport calculations with SLIMCAT, and with a reverse trajectory model driven with several meteorological analyses, fail to reproduce the remarkable persistence of the FrIAC, showing it to shear out and disappear by early June.

The formation and persistence through late May of the anticyclone are seen in PV fields from several meteorological analyses, but the PV feature disappears in early June. Although this may be partly related to the differing effect of diabatic processes on PV and chemical tracers, the inability of transport calculations to preserve the FrIAC suggests that it may also be related to deficiencies in detail in summer high-latitude horizontal winds, which would be reflected in PV.

An obvious question is how common are these occurrences. Unfortunately, the feature is not as persistent in PV fields, which are the only long-term record for trying to identify previous occurrences. Also, the PV fields from different analyses vary significantly in their ability to represent the FrIAC even in the earlier stages, with the lower resolu-

tion analyses from the MO (more similar to PV fields that are available in the long-term record) providing a less distinct view than those from current-day ECMWF or GEOS-4 fields. Nevertheless, we have examined the PV record in spring using MO PV back through 1991 and ECMWF ERA-40 PV back through 1958. We have identified several years in which the PV fields suggest that a FrIAC may have occurred (that is, when a tongue of low latitude air was drawn into a high-latitude anticyclone shortly before the general wind reversal, and a PV signature persisted until late May). The most distinct features were in 1982, 1994 and 2003; 1997 and 2002 PV fields also suggest that a FrIAC may have occurred. This suggests that a FrIAC is probably not uncommon, though certainly not an annual phenomenon. Although the Cryogenic Limb Array Etalon Spectrometer (CLAES) on the Upper Atmosphere Research Satellite observed long-lived tracers during parts of spring 1992 and 1993, PV fields in those years do not indicate conditions favorable for a FrIAC to form, and there is no indication of a FrIAC signature in CLAES data. We will look for evidence of a FrIAC in 2003 in MIPAS (Michelson Interferometer for Passive Atmospheric Sounding on ENVISAT) data. While there may be some evidence of such features in previous sparser datasets (such as those from high-latitude solar occultation instruments), the nature of the FrIAC – the lack of a persistent signature in O<sub>3</sub> or PV, small geographic extent, and rapid motion – is such that it is unlikely that this phenomenon could have been reliably identified without global or hemispheric daily profile measurements of long-lived trace gases such as those from EOS MLS. Identification of the FrIAC phenomenon provides new insight into transport processes in the spring and summer polar stratosphere, and has the potential to provide information to improve our knowledge of stratospheric winds and our ability to model transport.

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